

EVOLUTION ON THE AGB AND BEYOND: ON THE FORMATION OF H-DEFICIENT POST-AGB STARS

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Abstract. The evolution on the AGB and beyond is reviewed with respect to the origin of Wolf-Rayet central stars. We focus on thermal pulses due to their particular importance for the evolution of hydrogen deficient stars. It is shown that overshoot applied to all convection regions is a key ingredient to model these objects leading to intershell abundances already close to the surface abundances of Wolf-Rayet central stars. In contrast to standard evolutionary calculations, overshoot models do show dredge up for very low envelope masses and efficient dredge up was found even during the post-AGB stage. Three thermal pulse scenarios for Wolf-Rayet central stars can now be distinguished: an AGB Final Thermal Pulse (AFTP) occurring at the very end of the AGB evolution, a Late Thermal Pulse (LTP) occurring during the post-AGB evolution when hydrogen burning is still on, and a Very Late Thermal Pulse (VLTP) occurring on the cooling branch when hydrogen burning has already ceased. All scenarios lead to hydrogen-deficient post-AGB stars with carbon and oxygen abundances as observed for Wolf-Rayet stars. Hydrogen is either diluted by dredge up (AFTP, LTP) or completely burnt (VLTP).

1. Introduction

The origin of hydrogen-deficient post-Asymptotic-Giant-Branch (post-AGB) stars has been a matter of debate since many years. Although stars evolving through the AGB phase stay hydrogen-rich at their surfaces, a considerable fraction of their descendants, the central stars of planetary nebulae (CSPNe), show hydrogen-deficient compositions (Mendez 1991). Approximately 20% of the whole CSPNe population appears to be hydrogen deficient while the rest show solar-like compositions. Whereas we believe to

understand the structure and evolution of the latter with normal surface abundances reasonably well, the evolution of the former appeared to be still enigmatic. Important constituents of the hydrogen-deficient population are the so-called Wolf-Rayet (WR) central stars and the hot PG 1159 stars with typical surface abundances of (He,C,O)=(33,50,17) by mass (Dreizler & Heber 1998, Koesterke & Hamann 1997). In addition to their exotic abundances, WR CSPNe expose strong stellar winds of $\sim 10^{-6} M_{\odot}/\text{yr}$ and higher PN outflow velocities but otherwise do not differ significantly from the rest of the central stars (Gorny & Stasinska 1995, Tylenda 1996) and are expected to have the same mean mass of $\sim 0.6 M_{\odot}$ (Szczerba et al. 1998). Standard stellar evolution calculations predict post-AGB stars either to have hydrogen-rich surfaces (e.g. Vassiliadis & Wood 1994, Blöcker 1995b) or, if hydrogen-deficient, to expose only a few percent of oxygen in their photospheres (Iben & McDonald 1995), and thus appropriate models for WR CSPNe are still lacking.

Three types of evolutionary scenarios have been invoked to explain the Wolf-Rayet central stars. The first assumes the Wolf-Rayet stars to be the products of binary evolution with a common envelope phase (Tylenda & Gorny 1993) but appears to be unlikely because binarity is not observed. The other scenarios assume that they are either formed by a final thermal pulse during their post-AGB evolution or directly emerge from the AGB.

2. Evolution along the AGB

Stars with initial masses between 0.8 and $6-8 M_{\odot}$ evolve after completion of central hydrogen and helium burning through the AGB phase consisting then of a compact carbon/oxygen core ($\sim 0.5-1 M_{\odot}$) surrounded by a thin layer of some $10^{-2} M_{\odot}$ occupied by two shells burning helium and hydrogen, resp., and a huge, almost fully convective envelope. Although being short the AGB phase is of essential importance since it is governed by a rich nucleosynthesis, various processes which mix up processed material from the interior to the surface, and strong stellar winds, which substantially erode the stellar surfaces thereby continuously enriching the interstellar medium with heavier elements. This concerns in particular the evolution on the upper AGB which is dominated by continuously increasing mass loss (see Habing (1996) for a review). Observations indicate rates of $10^{-7} M_{\odot}/\text{yr}$ for small-period Mira stars and up to $10^{-4} M_{\odot}/\text{yr}$ for luminous long-period variables (Wood 1997). These winds are most likely driven by dust and shocks (Winters 1998) leading at larger mass-loss rates to the complete obscuration of the star by a dusty circumstellar envelope.

Concerning mixing processes and nucleosynthesis, thermal instabilities of the helium burning shell (thermal pulses) and the possible penetration

of the convective envelope into the hydrogen burning shell (hot bottom burning, HBB) are crucial for the evolution on the upper AGB.

Hot bottom burning is restricted to more massive stars ($M \gtrsim 4M_{\odot}$). Temperatures in excess of $50 \cdot 10^6$ K can be reached at the base of the convective envelope and material burnt there is immediately mixed to the surface leading, for instance, to the formation of lithium-rich AGB stars (Scalo et al. 1975). HBB models do not obey Paczynski's (1970) classical core-mass luminosity relation but, instead, evolve rapidly to very high luminosities (Blöcker & Schönberner 1991). Due to CN cycling of the envelope ^{12}C can be transformed into ^{13}C and ^{14}N . Consequently, a low $^{12}\text{C}/^{13}\text{C}$ ratio is a typical signature of HBB that can delay or even prevent AGB stars from becoming carbon stars (Iben 1975; Boothroyd et al. 1993). Finally, when mass loss has substantially reduced the envelope mass, the envelope convection moves upwards again and HBB shuts down (see Blöcker 1995a). Planetary nebulae showing abundance patterns with the signature of former HBB are discussed in, e.g. Kaler & Jacoby (1989) and Clegg (1991).

In the following we want to focus on thermal pulses due to their particular relevance for the origin and evolution of Wolf-Rayet central stars. A more general review of the AGB evolution is given in Blöcker (1999).

2.1. THERMAL PULSES AND THIRD DREDGE UP

On the upper AGB the helium burning shell becomes recurrently unstable raising the so-called thermal pulses (Schwarzschild & Härm 1965, Weigert 1966). During these instabilities the luminosity of the He shell increases rapidly for a short time of 100 yr to 10^6 to $10^8 L_{\odot}$. The huge amount of energy produced forces the development of a pulse-driven convection zone which mixes products of He burning, i.e. carbon and oxygen, into the intershell region. Because the hydrogen shell is pushed concomitantly into cooler domains hydrogen burning ceases temporarily allowing the envelope convection to proceed downwards after the pulse, to penetrate those inter-shell regions formerly enriched with carbon (and oxygen) and to mix this material to the surface. This 3rd dredge up leads finally to the formation of carbon stars. After the pulse hydrogen burning re-ignites and provides again the main source of energy. Typically, a thermal-pulse cycle last a few 10^3 yr for large core masses ($\gtrsim 0.8M_{\odot}$) and 10^4 yr to 10^5 yr for smaller ones. Fig. 1 shows the evolution of the luminosities of the hydrogen and helium burning shells during the thermal pulses of a $3 M_{\odot}$ AGB sequence.

2.2. THE ROLE OF OVERSHOOT

The formation of carbon stars and its modelling by stellar evolution calculations has been a long-standing problem. Early stellar evolution calculations

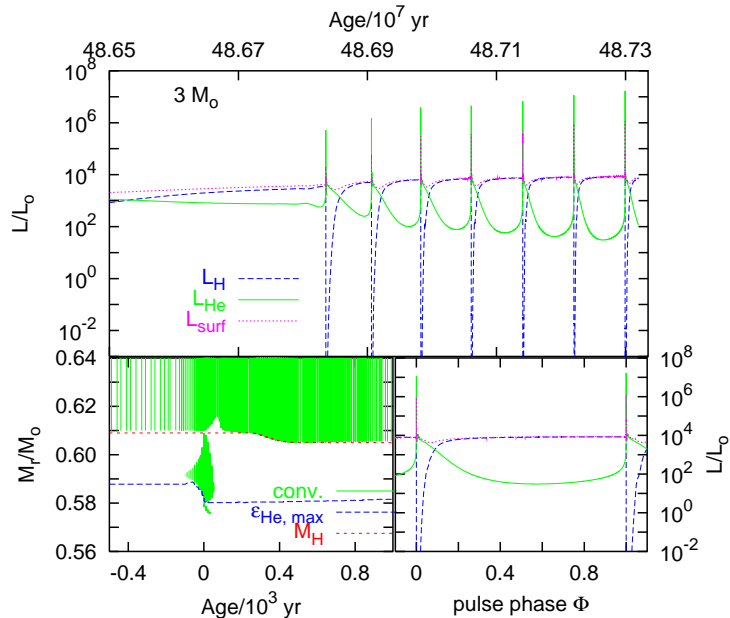


Figure 1. Evolution of the surface luminosity and the luminosities of the H and He burning shell during the first thermal pulses of a $3 M_{\odot}$ AGB sequence (top). The lower left panel gives the extension in mass of convective regions during the sixth pulse cycle. It shows the formation of the pulse-driven convection zone and the following dredge-up phase. Time is set to zero at maximum L_{He} . M_H refers to the mass of the H exhausted core, and $\epsilon_{He, max}$ to max. energy generation of He burning. The lower right panel shows the luminosity evolution as a function of the thermal pulse phase during this cycle. Note that the left panel refers only to phases of $\phi \sim 0.99$ to 0.01.

predicted dredge up mostly for large core-masses, i.e. high luminosities, whereas most of the (LMC) carbon stars observed are found at low luminosities and, therefore, are of lower mass (*carbon star mystery*, Iben 1981). Moreover, various evolutionary calculations did not find dredge up at all or differ in the efficiency obtained (e.g. Vassiliadis & Wood 1993, Blöcker 1995a, Forestini & Charbonnel 1997). The lack of optically bright carbon stars can be explained in terms of hot bottom burning and mass loss. HBB counteracts the carbon star formation. However, since it ceases earlier than dredge up, final dredge-up episodes may still produce carbon stars in the end (Frost et al. 1998). Due to mass loss such luminous carbon stars are expected to be heavily enshrouded by dust hiding them from optical surveys. Indeed, infrared observations of van Loon et al. (1999) show evidence for the existence of luminous obscured (MC) carbon stars. The failure to obtain efficient dredge up, in particular for lower-mass AGB models, is related to the only approximate description of stellar convection and accordingly to the treatment of convective boundaries. Another question intimately linked

to this problem is how to produce sufficient amounts of ^{13}C in the interior as the neutron source for the s -process nucleosynthesis. Therefore, it is often concluded that mixing may take place outside the formally convective boundaries (Iben 1976, D’Antona & Mazzitelli 1996, Wood 1997).

To overcome these problems Herwig et al. (1997) have considered diffusive overshoot for all convective boundaries during the complete evolution leading to a considerable change in the models. The overshoot prescription is based on the hydrodynamical calculations of Freytag et al. (1996) who showed that mixing takes place well beyond the classical Schwarzschild border due to overshooting convective elements with an exponentially declining velocity field. In the overshoot region the corresponding diffusion coefficient is given by $D_{\text{os}} = v_0 \cdot H_p \cdot \exp \frac{2z}{f \cdot H_p}$ with v_0 : velocity of the convective elements immediately before the Schwarzschild border; z : distance from the edge of the convective zone; f : the overshoot efficiency parameter. Within the stellar evolution calculations the efficiency parameter was chosen to be $f = 0.016$ as appropriate to match the observed width of the main sequence. This method provides for AGB stars a sufficient amount of dredge up to form low-mass carbon stars as required by the observations. Additionally it leads to the formation of ^{13}C as a neutron source to drive the s -process in these stars (see also Herwig et al. 1999a).

On the one hand, these calculations show that dredge up can easily be obtained if some envelope overshoot is present to overcome the H/He discontinuity by deepening the envelope convection. On the other hand, overshoot leads also to an enlargement of the pulse-driven convection zone and to enhanced mixing of core material from deep layers below the He shell to the intershell zone (“intershell dredge-up”) resulting in a considerable change of the intershell abundances. After intershell dredge up the abundances (mass fractions) of (He,C,O) amount typically to (40,40,16) instead of (70,25,2) as in non-overshoot sequences. It is important to note that the total amount of dredge up depends mainly on the strength of the former intershell dredge-up (Herwig et al. 1999a). These modified intershell abundances are close to the observed surface abundances of Wolf-Rayet central stars (Koesterke, this volume) and PG 1159 stars (Werner, this volume) and will turn out to be a key ingredient for the modelling of these objects.

3. Evolution beyond the AGB

Mass loss terminates the AGB evolution when the envelope mass is reduced to $\approx 10^{-2} M_{\odot}$. The star moves off the AGB (Schönberner 1979) evolving towards the regime of central stars of planetary nebulae and finally reaches the stage of white dwarfs. Fig. 2 illustrates the evolution of an initially $3 M_{\odot}$ star from the main sequence to the white dwarf stage. Recent reviews on

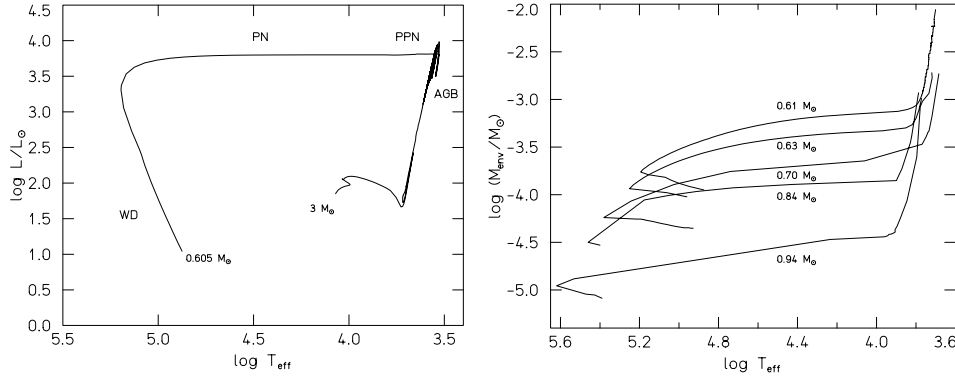


Figure 2. Left: Evolutionary path for an initially $3 M_{\odot}$ star from the main sequence to the white-dwarf stage. The last thermal pulses at the tip of the AGB are clearly visible. The model is burning hydrogen until the shell source gets extinct. The final mass is $0.605 M_{\odot}$. Right: Envelope mass vs. effective temperature for hydrogen burning post-AGB models (Blöcker 1995b). The initial and remnant masses are $(3 M_{\odot}, 0.61 M_{\odot})$, $(3 M_{\odot}, 0.63 M_{\odot})$, $(4 M_{\odot}, 0.70 M_{\odot})$, $(5 M_{\odot}, 0.84 M_{\odot})$, and $(7 M_{\odot}, 0.94 M_{\odot})$, resp. (from top to bottom).

the structure and evolution of central stars of planetary nebulae are given, e.g., by Iben (1995) and Schönberner and Blöcker (1996).

3.1. MASS LOSS

One important aspect of the transformation of AGB stars into white dwarfs is the treatment of mass loss on the AGB and beyond. On the one hand, the AGB mass-loss history determines the star's internal structure reached at the tip of the AGB and therefore the fading speed along the cooling part of the post-AGB evolution (Blöcker 1995a,b). On the other hand, the transition times from the AGB to the central-star region depend sensitively on the mass-loss rates employed beyond the AGB (Schönberner 1983). Observations indicate that mass-loss should decrease by order of magnitudes during this transition phase (Perinotto 1989). However, up to now it is only poorly known how and at which temperature (range) this strong decrease takes place. The transition times should not be too long since the coolest post-AGB stars known have effective temperatures of about 5000 K (Schönberner & Blöcker 1993), and kinematical ages of the youngest planetaries are only of the order of 1 000 years. Fig. 2 shows the envelope mass for different remnant masses as a function of the effective temperature.

In the PN region mass-loss can be described by the radiation-driven wind theory (Pauldrach et al. 1988). The respective mass-loss rates can be adapted like $\dot{M}_{\text{CPN}} = 1.3 \cdot 10^{-15} L^{1.9}$ (Blöcker 1995b), leading to rates of

10^{-8} to $10^{-7} M_{\odot}/\text{yr}$ for remnants of 0.6 to $0.8 M_{\odot}$. The corresponding influence on the evolutionary speed depends on the respective ratio of the burning rate to mass-loss rate and is only important for massive remnants. For H burning objects the total crossing time of the lighter central stars is therefore uniquely given by the available fuel (i.e. the envelope mass) divided by the hydrogen luminosity. Because the envelope mass decreases and the luminosity increases with remnant mass, one obtains typical crossing times (between $10\,000$ K to the turn-around point in the HRD) of $\sim 100\,000$ yr for $0.55 M_{\odot}$, 4000 yr for $0.6 M_{\odot}$, and 50 yr for $0.94 M_{\odot}$.

When hydrogen burning cannot be sustained any longer because the envelope mass becomes too small, the surface luminosity must drop very fast by at least one order of magnitude until it can be covered by gravothermal energy releases. Helium burning is unimportant for most phase angles and dies away as well. The fading time of AGB remnants down to, for instance, $100 L_{\odot}$ is thus controlled by the gravothermal energy release and neutrino energy losses. Both processes depend on the thermomechanical structure of the core, and thus on the complete evolutionary history.

3.2. FINAL THERMAL PULSES

The evolution off and beyond the AGB depends also on the thermal-pulse cycle phase (fraction of the time span between two subsequent pulses) ϕ with which the star moves off the AGB. The post-AGB evolution is dominated by helium burning for $0 \leq \phi \leq 0.15$. For $0.15 \leq \phi \leq 0.3$ both nuclear shell sources contribute equal luminosity fractions, for $0.3 \leq \phi \leq 1.0$ hydrogen burning determines the nuclear energy production (Iben 1984). If the thermal-pulse cycle-phase is sufficiently large, a last thermal pulse can occur during the post-AGB evolution transforming a hydrogen burning into a helium burning model. The flash forces the star to expand rapidly to Red Giant dimensions, and the remnant quickly evolves back to the AGB (“born again scenario”). There, it starts its post-AGB evolution again, but now as a helium burning object (Iben 1984). The crossing timescale is now roughly three times larger than in the case of hydrogen burning objects. In principle we can distinguish three scenarios of final thermal pulses relevant for Wolf-Rayet CSPNe (see also Herwig, this volume):

1. The “AGB final” thermal pulse (AFTP), occurring immediately before the star moves off the AGB. In this case the envelope mass is already very small ($\sim 10^{-2} M_{\odot}$, Fig. 2). If dredge up is able to operate even for such small envelope masses, a substantial fraction of the intershell region will be mixed with the tiny envelope leading to the dilution of hydrogen and enrichment with carbon and oxygen. However, standard evolutionary calculations predict a decreasing dredge-up efficiency for

low envelope masses (Wood 1981) and lack a sufficiently high oxygen abundance in the intershell region.

2. The “late” thermal pulse (LTP), occurring when the model evolves with roughly constant luminosity from the AGB towards the white dwarf domain. This kind of thermal pulse is similar to those experienced by AGB stars but the envelope mass is even smaller than for the AFTP ($\sim 10^{-4}M_{\odot}$, Fig. 2). Evolutionary calculations without overshoot (e.g. Blöcker & Schönberner 1997) predict only mild, if any, mixing. The envelope convection does not reach the layers enriched with carbon, and no 3rd dredge up occurs. Therefore, this scenario has often been considered in connection with mass loss, which, however, cannot expose the hydrogen-free layers before effective temperatures of 100000 K are reached (Iben 1984, Schönberner & Blöcker 1992).
3. The “very late” thermal pulse (VLTP), occurring when the model is already on the white dwarf cooling track, i.e. after the cessation of H burning. In this case the pulse-driven convection zone of the He-burning shell may reach and penetrate the H shell causing a considerable or even total burning of hydrogen (Fujimoto 1977, Schönberner 1979, Iben 1984, Iben & McDonald 1995). Due to mixing of the very tiny envelope ($\lesssim 10^{-4}M_{\odot}$, Fig. 2) with substantial fractions of the 100 times more massive intershell region, the resulting surface abundances of carbon and oxygen are close to those of the intershell region. This scenario has been considered as the most promising one for Wolf-Rayet CSPNe although it failed to match the observed oxygen abundances.

In summary one may conclude that within standard evolutionary calculations neither the AFTP nor the LTP or VLTP appear to be well suited scenarios for Wolf-Rayet stars leaving these stars still enigmatic. However, the consideration of overshoot leads to a considerable change in the models making these scenarios much more promising.

3.3. AGB FINAL THERMAL PULSE (AFTP)

If overshoot is applied to all convective regions, AGB models show efficient dredge up even for very low envelope masses (see Herwig, this volume). Then, an AFTP can lead to both a considerable enrichment with carbon and oxygen and to the dilution of hydrogen. The resulting surface abundances depend on the actual envelope mass at which the AFTP occurs. For instance, Herwig (this volume) found for $M_{\text{env}} = 4 \cdot 10^{-3}M_{\odot}$ (H,He,C,O)=(17,33,32,15) after the AFTP. The smaller M_{env} , the closer are the final abundances to those observed in WR CSPNe. To obtain a sufficiently high probability for the AFTP to occur at very small envelope masses (i.e. at $\phi \approx 0$) requires, however, a coupling of mass loss to the ther-

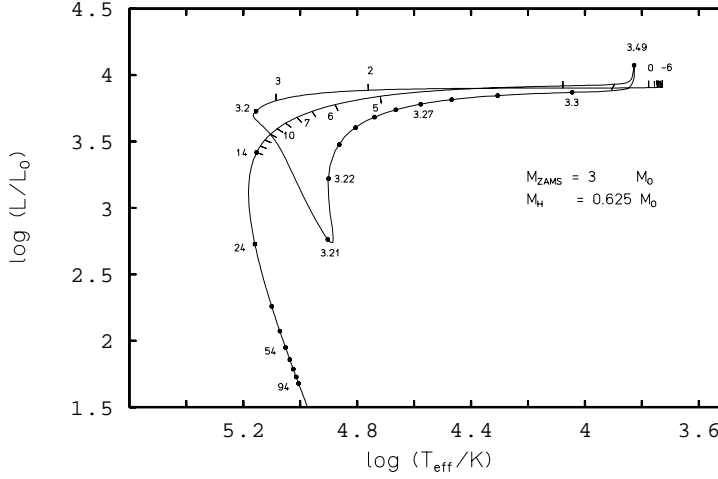


Figure 3. Evolution of a post-AGB model with $M_{\text{ZAMS}} = 3M_{\odot}$ and $M_{\text{H}} = 0.625M_{\odot}$ suffering from a LTP (Blöcker 1995b). Age zero refers to a pulsational period of 50 d. Time marks are in units of 10^3 yrs.

mal pulse cycle. Otherwise, the hydrogen abundance will be relatively high. This scenario predicts small kinematical ages for the PNe of WR central stars which emerge here directly from the AGB.

3.4. LATE THERMAL PULSE (LTP)

The LTP, occurring for stars which leave the AGB with $\phi \gtrsim 0.85$, have only been considered in connection with mass loss to explain the exotic surface abundances of WR CSPNe since dredge up is lacking. In contrast to hydrogen burning objects where high mass loss leads to a strong acceleration of the evolution limiting the removable mass, the longer evolutionary timescales of helium burning objects allow to expose the H-free layers, although only for T_{eff} in excess of 100000 K. To strip off enough mass to expose even the deep layers which match the observed carbon and oxygen abundances requires long lasting stellar winds. Although this scenario appears not to be applicable to WR CSPNe, it may have some relevance for the most exotic PG 1159 star H 1504. H 1504 populates the cooling branch and shows a photosphere containing only carbon and oxygen with 50% each (see Werner, this volume). An exploratory study of Schönberner & Blöcker (1992) showed that the photospheric parameters (T_{eff} , $\log g$, surface abundances) of H 1504 can be matched with a $0.84M_{\odot}$ LTP model suffering

from a constant mass-loss rate of $10^{-7} M_{\odot}/\text{yr}$ until the position of H 1504 in the HRD is reached. It is an open question if such high mass-loss rates can be kept on the low luminosity part of the cooling branch. However, recent studies of Werner et al. (1995) give evidence that hot white dwarfs may indeed suffer from such strong stellar winds.

So far, stellar evolution calculations did not show any dredge up mixing carbon to the surface within the LTP scenario. However, if overshoot is considered, efficient dredge up operates even for $M_{\text{env}} \lesssim 10^{-4} M_{\odot}$. These new models show for the first time that the LTP scenario may serve as one possible channel for the WR CSPNe. We note that, as in the case of the AFTP, overshoot applied to the pulse-driven convection zone is essential for the resulting dredge-up efficiency. We have applied the overshoot scheme of Herwig et al. (1997) to the post-AGB models of Blöcker (1995b) which are based on an AGB evolution without overshoot. Herwig et al. (1999a) have shown that the intershell abundances of carbon and oxygen first increase and then level out after a series of thermal pulses for overshoot AGB models. To account for these typical intershell abundances, we recalculated the LTP of Blöcker's (1995b) $0.625 M_{\odot}$ model with an enhanced overshoot efficiency ($f=0.064$) for the pulse-driven convection zone leading to $(\text{He}, \text{C}, \text{O})=(45, 40, 13)$ in the intershell region. For the remaining evolution the standard efficiency parameter of $f=0.016$ was used. This method provides a simulation close to an object where overshoot have been applied during the whole preceding AGB evolution. Fig. 4 shows the abundances of H, He, C and O for the initial model and immediately after the flash.

After the flash (and two subpulses, see Fig. 5) the model evolves towards the AGB domain. At minimum effective temperature (≈ 6700 K) dredge up sets in and continues until the star has reheated to ≈ 12000 K. Hydrogen is diluted to 3% and the final surface abundances of He, C and O are close to those of the intershell region, viz. $(45, 38, 12)$. Extension of convective regions and abundances are illustrated in Fig. 5 as function of age and effective temperature, resp. We obtain surface abundances as observed in WR CSPNe (cf. Koesterke, this volume). The kinematical age of the PN amount to a few thousand years (see Fig. 3).

This scenario applies to FG Sge as well that suffered from a LTP roughly 100 yr ago. FG Sge seems to have already reached its minimum effective temperature and to reheat now again (Kipper 1996). Its mass can be estimated to be close to $0.6 M_{\odot}$ and its surface stays hydrogen-rich during its evolution back to the AGB (excluding a VLTP, Blöcker & Schönberner 1997). However, recently evidence is growing that FG Sge becomes hydrogen-deficient during its reheating (Gonzalez et al. 1998). This is hard to explain within the standard LTP scenario (no overshoot) but is completely in line with the predictions of the new models.

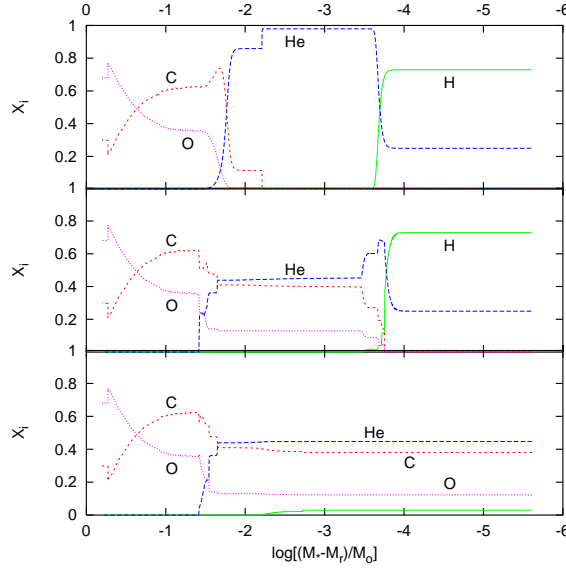


Figure 4. Abundances of H, He, C, and O as function of mass for a post-AGB model of $0.625 M_{\odot}$. The stellar center is left and the surface is to the right. The top panel shows the composition of the initial model calculated without overshoot on the AGB. The middle panel refers to the point of time after the flash calculated with enhanced overshoot efficiency as required to generate appropriate intershell abundances. The situation after the dredge up is shown in the lower panel.

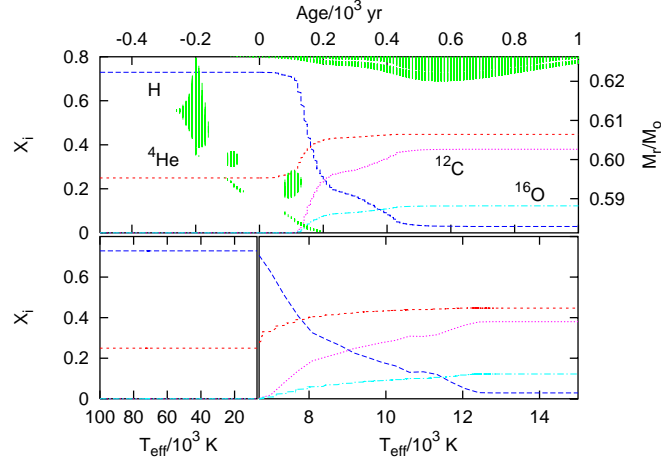


Figure 5. Evolution of the surface abundances of H, He, C, and O and extension of convective regions for the $0.625 M_{\odot}$ model during the flash and dredge up (top). Shaded regions denote convective regions. Time is set to zero at minimum effective temperature. The lower panel gives the corresponding evolution for the abundances as function of the effective temperature.

3.5. VERY LATE THERMAL PULSE (VLTP)

The VLTP is different from the AFTP and LTP since it causes a burning (and mixing) of the envelope requiring more demanding numerics. The only model available until recently was that of Iben & McDonald (1995) which shows strong hydrogen deficiency after the flash but too low oxygen surface abundances as to account for the WR CSPNe. Herwig et al. (1999b) presented the first VLTP model which achieves a general agreement with the abundance patterns of WR CSPNe due to the consideration of overshoot. Again, the existence of intershell dredge-up providing intershell abundances close to those observed in photospheres of WR CSPNe appeared to be crucial to match the observations (see also Herwig, this volume).

The VLTP occurs on the cooling track when H burning is already off. In this instance, the pulse-driven convection zone can reach and penetrate the H-rich envelope due to the lack of an entropy barrier (Iben 1976) built up by H burning. Then, protons are ingested into the hot, carbon-rich intershell region and are captured via $^{12}\text{C}(\text{p},\gamma)^{13}\text{N}$. Convective turnover timescales and nuclear timescales become comparable during this phase, and the protons are burnt on their way towards the interior. Accordingly, a simultaneous treatment of mixing and burning is essential to treat this phase of evolution correctly. The ingestion of protons finally raises a H flash and the energy released by this flash leads to a splitting of the convection into a upper zone powered by H burning and a lower one powered by He burning. The upper convection zone is, however, short-lived because the available hydrogen in the envelope is quickly consumed. Finally, the star becomes hydrogen-free and exposes its intershell abundances at the surface.

Fig. 6 shows the evolutionary track of the 0.604 M_{\odot} model of Herwig et al. (1999b) which is based on a 2 M_{\odot} overshoot sequence. The dots on the track denote the establishment of the pulse-driven convection zone, the ingestion of protons, the peak of the H flash, and the moment when the surface becomes H-free. The resulting surface abundances are $(\text{He}, \text{C}, \text{O}) = (38, 36, 17)$. Among the remaining elements is Ne with 3.5%. Note that the burning of the envelope takes place at high effective temperatures and that no hydrogen survives. The kinematical age of the surrounding PN is relatively high within the VLTP scenario since the star has first to fade along the cooling branch down to a few 100 L_{\odot} before the onset of the flash. For 0.6 M_{\odot} one obtains typically $t \gtrsim 20000\text{ yr}$.

4. Concluding remarks

If overshoot is applied to AGB models, intershell dredge-up provides intershell abundances close to the surface abundances of Wolf-Rayet CSPNe and PG 1159 stars. These intershell abundances can be mixed to the surface

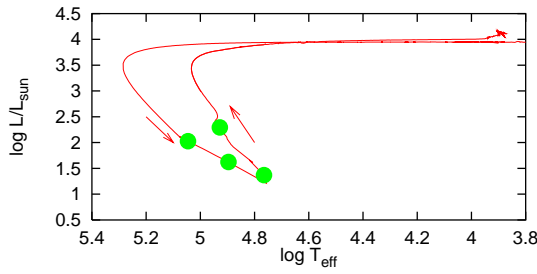


Figure 6. Evolutionary track of a $0.604 M_{\odot}$ post-AGB model ($M_{\text{ZAMS}} = 2 M_{\odot}$) suffering from a VLTP (Herwig et al. 1999b). The dots refer to the formation of the pulse-driven convection zone, to the ingestion of protons, to the peak of the induced H flash, and to the moment when all hydrogen is burnt leaving a hydrogen-free surface.

during the AFTP, LTP or VLTP scenario. In contrast to standard evolutionary calculations, overshoot models do show dredge up for very low envelope masses and efficient dredge up was found even during the post-AGB stage. All scenarios lead to hydrogen-deficient post-AGB stars with carbon and oxygen abundances as observed for Wolf-Rayet stars. Hydrogen is either diluted by dredge up (AFTP, LTP) or completely burnt (VLTP). The AFTP leads to a relatively high hydrogen abundance ($\gtrsim 15\%$) whereas the LTP gives only a few percent ($\lesssim 3\%$). The kinematical ages of the planetary nebulae are relatively high for the VLTP and are much lower for the AFTP and LTP scenarios. The variety of observations requires most likely all of these scenarios. Many objects have only very low hydrogen abundances, if any, favoring the LTP and VLTP. On the other hand, several Wolf-Rayet central stars are surrounded by young planetary nebulae (Tylenda 1996) and circumstellar shells (Waters et al. 1998) strengthening the AFTP and LTP. Within the current models roughly 20 to 25% of stars moving off the AGB can be expected to become hydrogen-deficient.

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